Correlation between Laser Absorption Process and Energy Conversion to Extreme Ultraviolet Radiation in Laser Produced Tin Plasma

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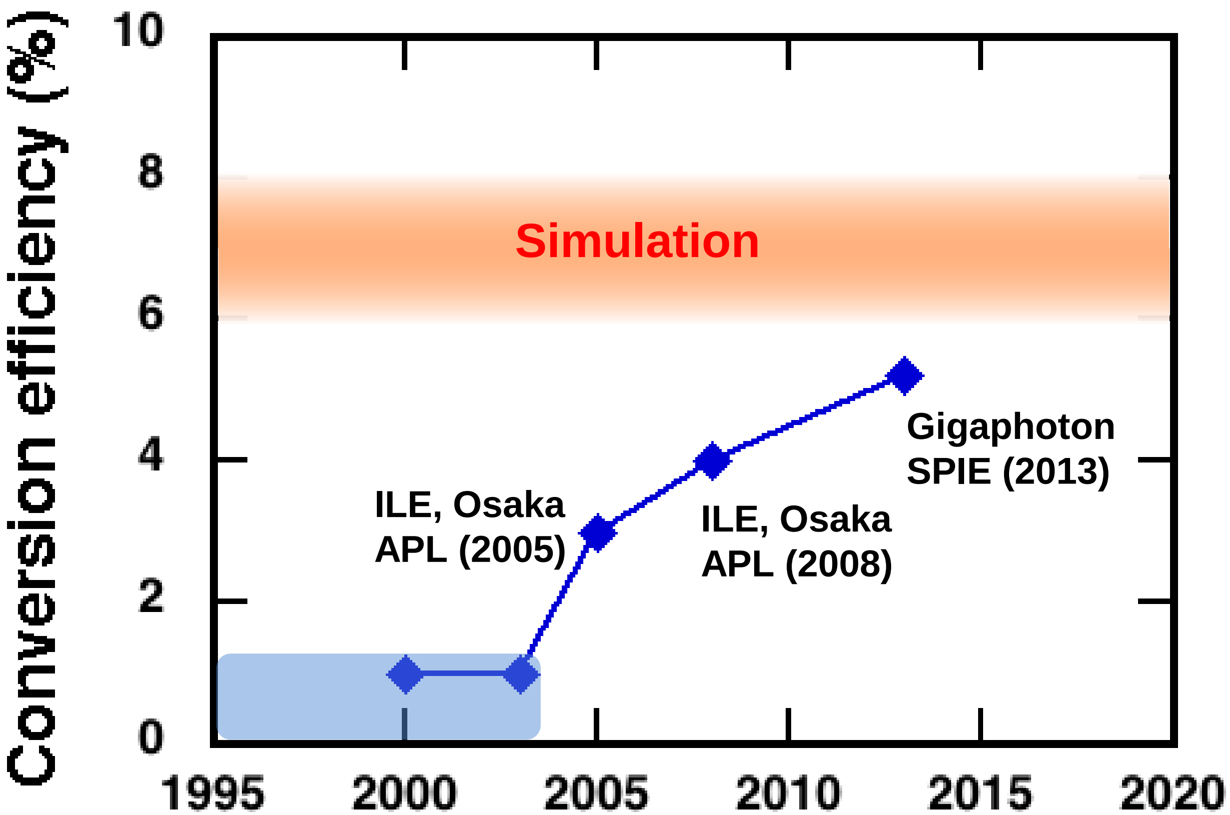
GIGAPHOTON

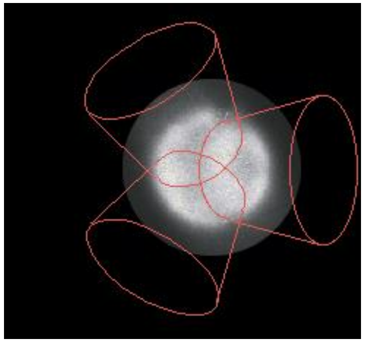
ILT

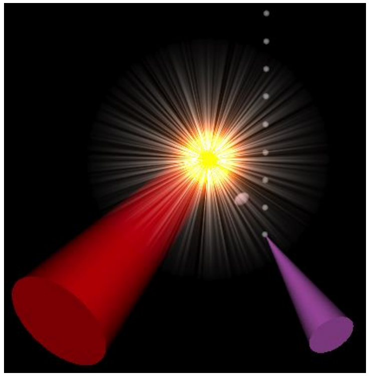
NEDO

PHOTON BEAM PLATFORM

Various studies for the highest possible conversion efficiency (CE) of EUV



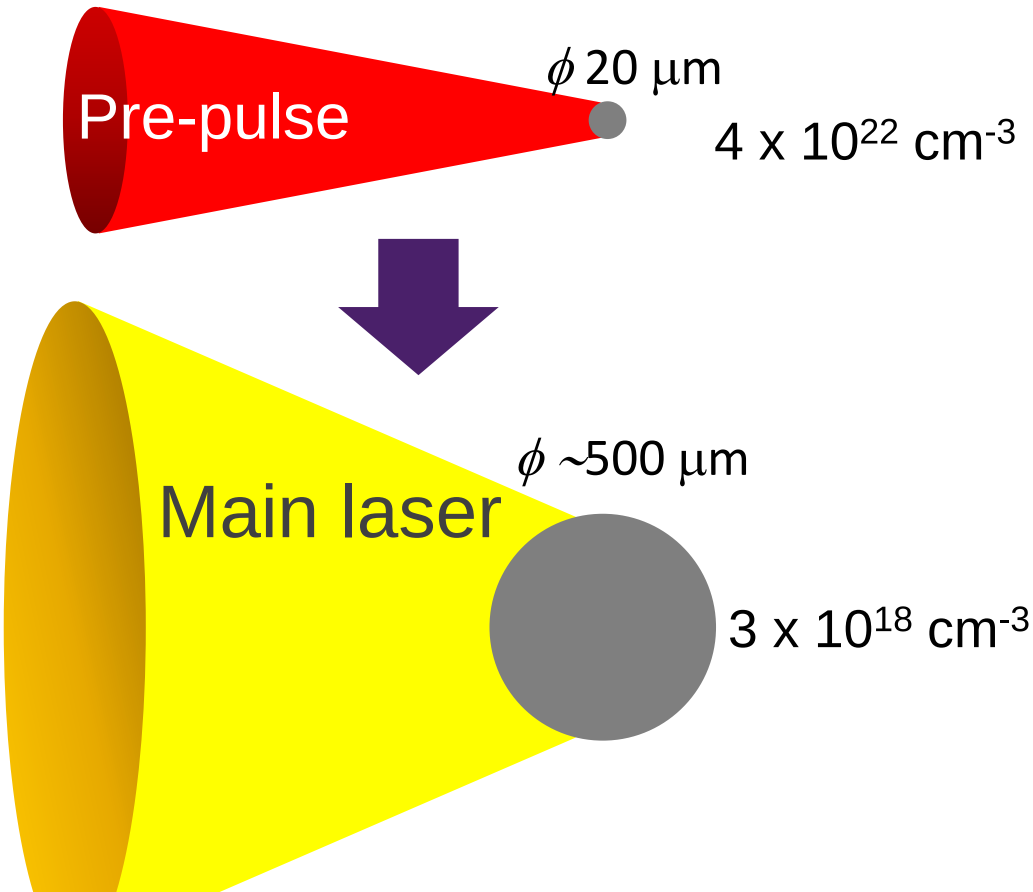

Spherical (2005)

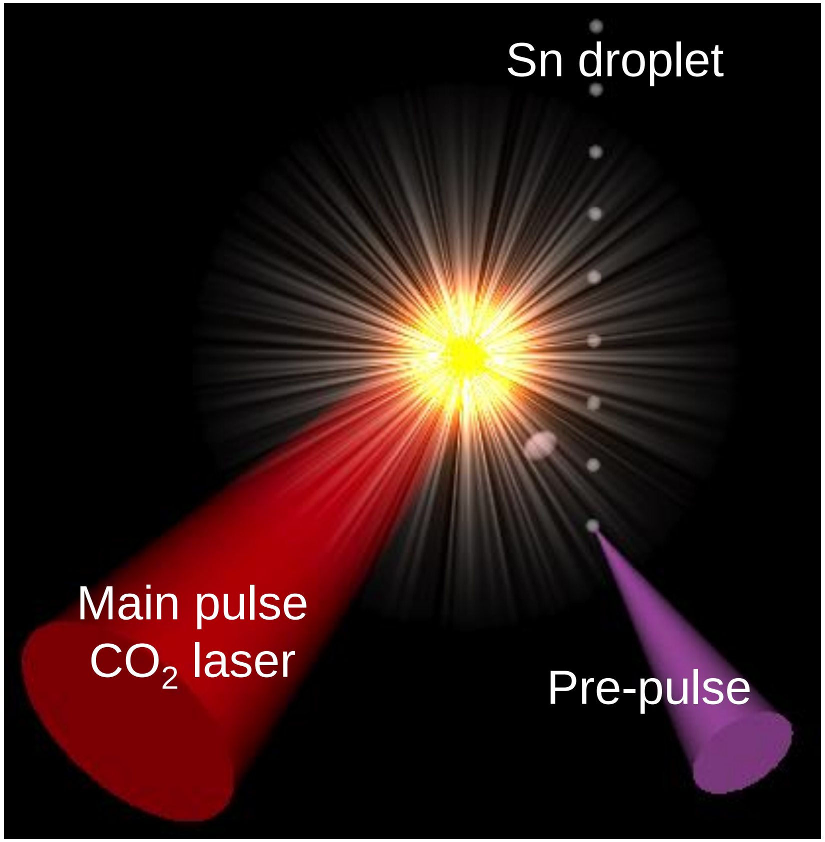

Double pulse (2008)

With ps pulse (2013)

Background

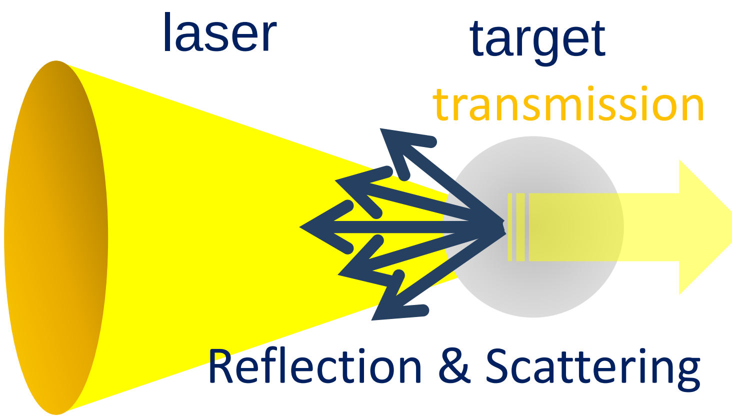
Two-color, double pulse scheme is widely adopted in EUV source for lithography





It has not been clarified yet
why CE is substantially increased, optimization plasma parameters or increase in laser absorption?

Elemental processes of laser produced plasma

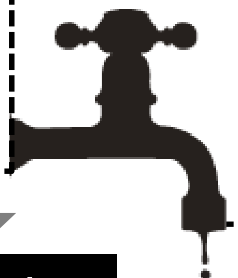


Absorption process

Ohmic heating

Inverse Bremsstrahlung

Collision and generation of hot electron



Kinetic energy

Internal energy

Radiation

Non-absorbed components

Reflection

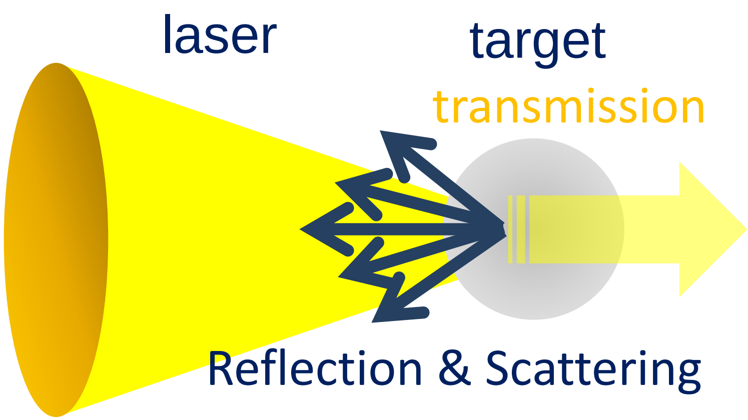
Scattering

Transmission

The method for measurement of absorption rate is presented.

Experiment

We developed an integrating sphere for measurement of absorption rate by plasma



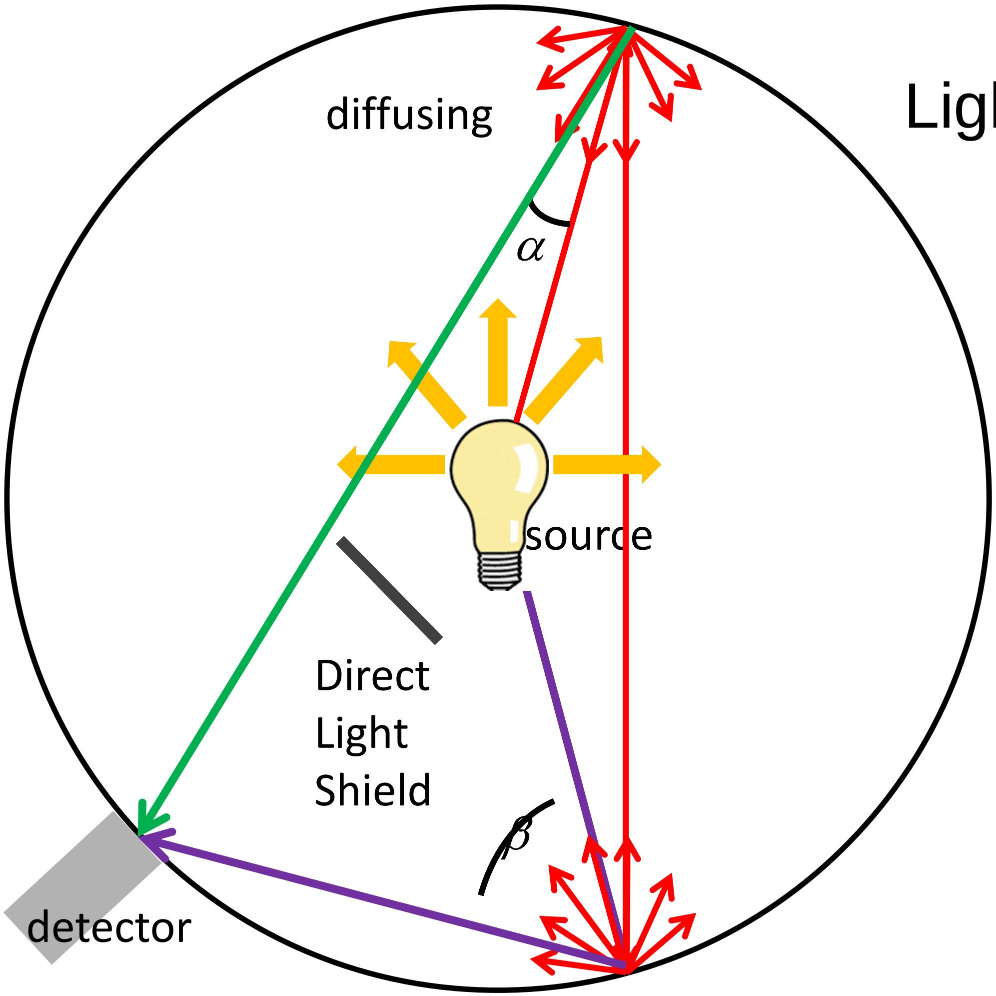
Integrating sphere

- Collecting specular and scattered light for 4π of solid angle
- NOT depending on angular distribution of light emission
- Proportional to light flux

$$\text{Absorption rate} = 1 - \frac{I_{\text{specular}} + I_{\text{scattered}}}{I_{\text{laser}}}$$

Experiment

Multi-reflection of scattered light homogenizes its distribution on the inner surface



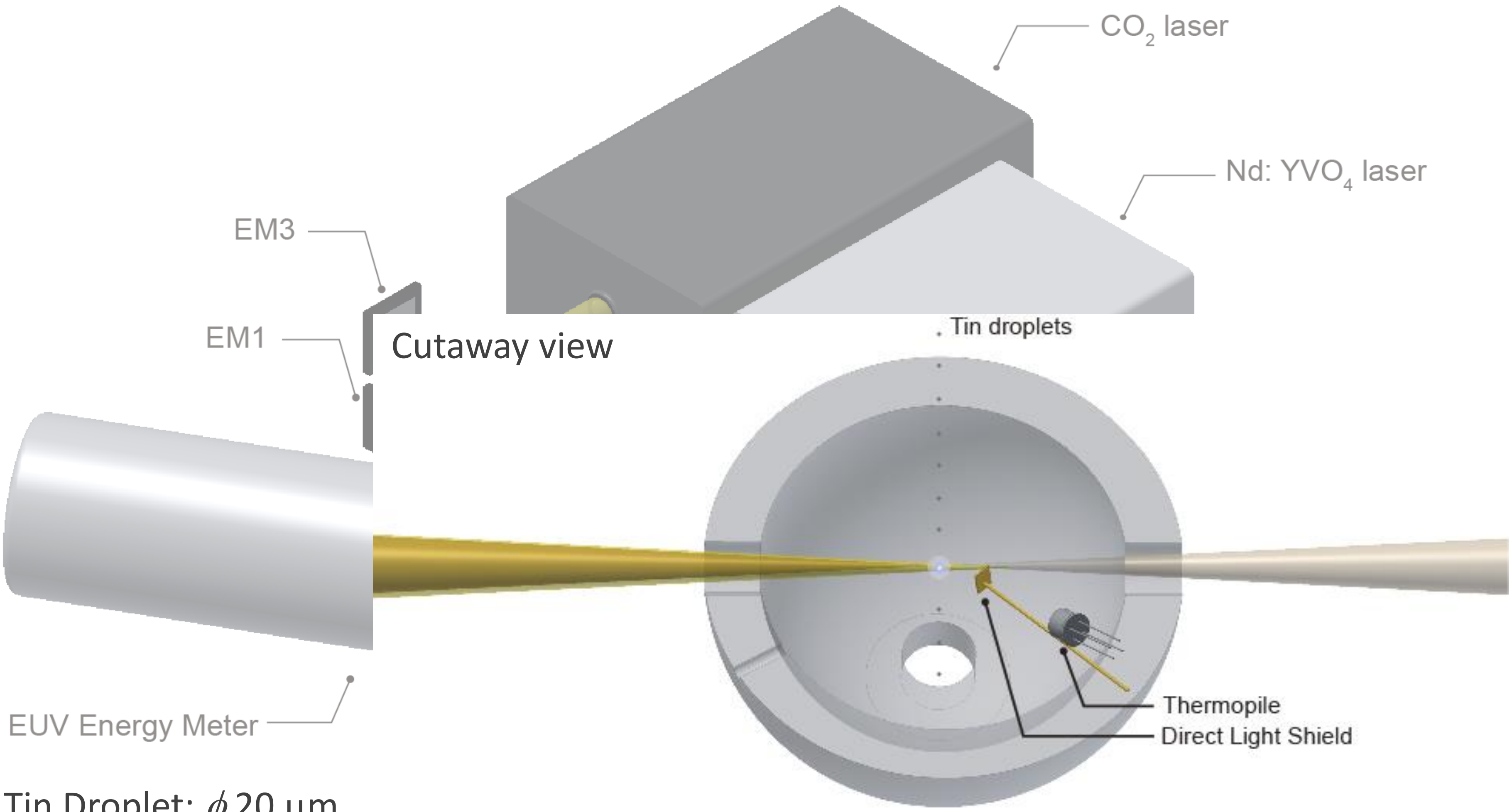
Light intensity @detector

$$= \frac{\rho\Phi}{S}(1+\rho+\rho^2+\rho^3+\rho^4+\ldots+\rho^{n-1})$$

$$= \frac{\Phi}{S}\frac{\rho}{1-\rho}$$

$\boldsymbol{\Phi}$: light source power
$\boldsymbol{\rho}$: diffuse reflection factor
S: surface area of integrating sphere

Experimental setup



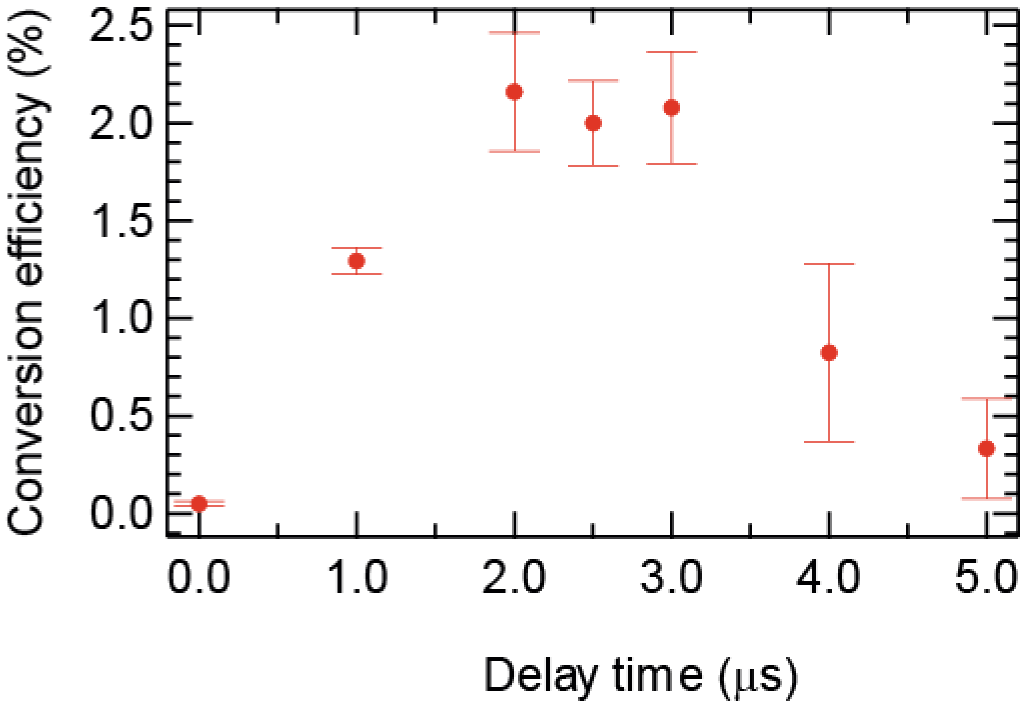
Tin Droplet: ϕ 20 μm

Nd:YVO$_4$ laser (Pre): λ = 1064 nm, 14 ps, 1.9 mJ, ϕ 77 μm (intensity $I_{pre} = 2.9 \times 10^{12}$ W/cm^2)

CO$_2$ laser (Main): λ = 10.6 μm, 14 ns, 100 mJ, ϕ 400 μm (intensity $I_{pre} = 5.7 \times 10^{9}$ W/cm^2)

Experiment

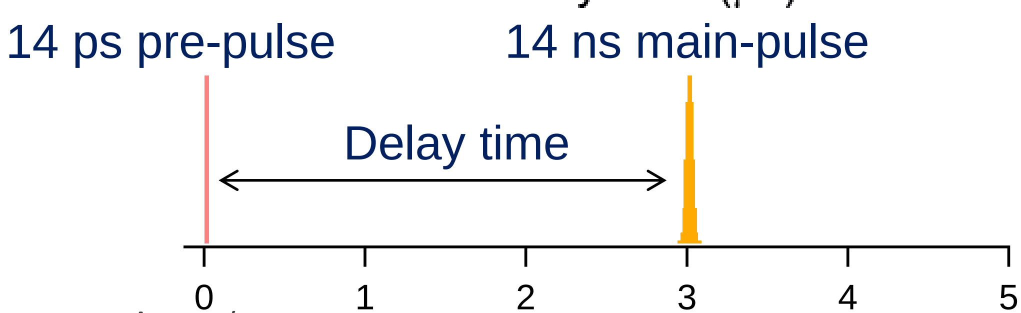
Timing-dependence of CE



$t < 2$ μs
increasing

$2 < t < 3$ μs
maximum

$t > 3$ μs
decreasing

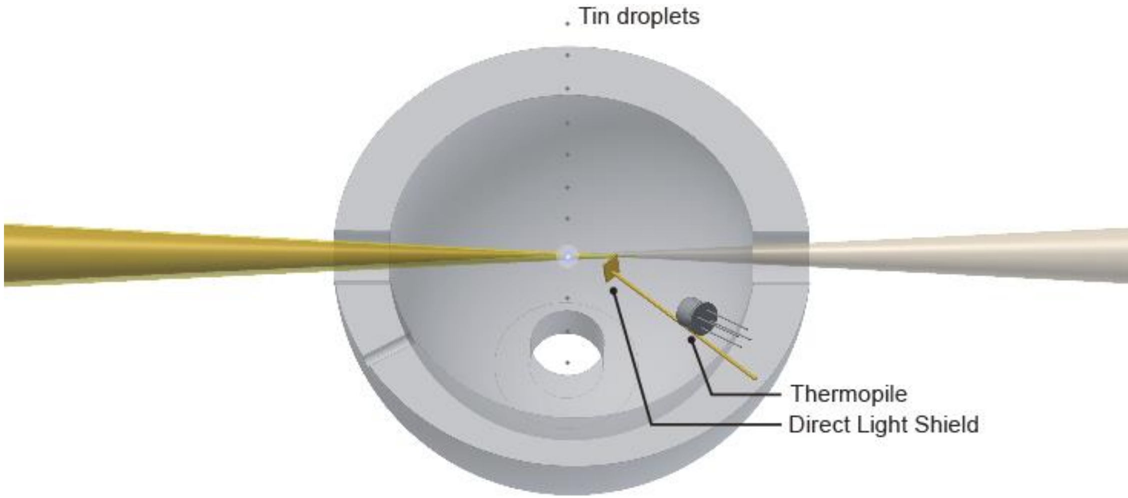


Tin Droplet: ϕ 20 μm

Pre-pulse: λ = 1064 nm, 14 ps, 1.9 mJ, ϕ 77 μm (intensity $I_{pre} = 2.9 \times 10^{12}$ W/cm^2)

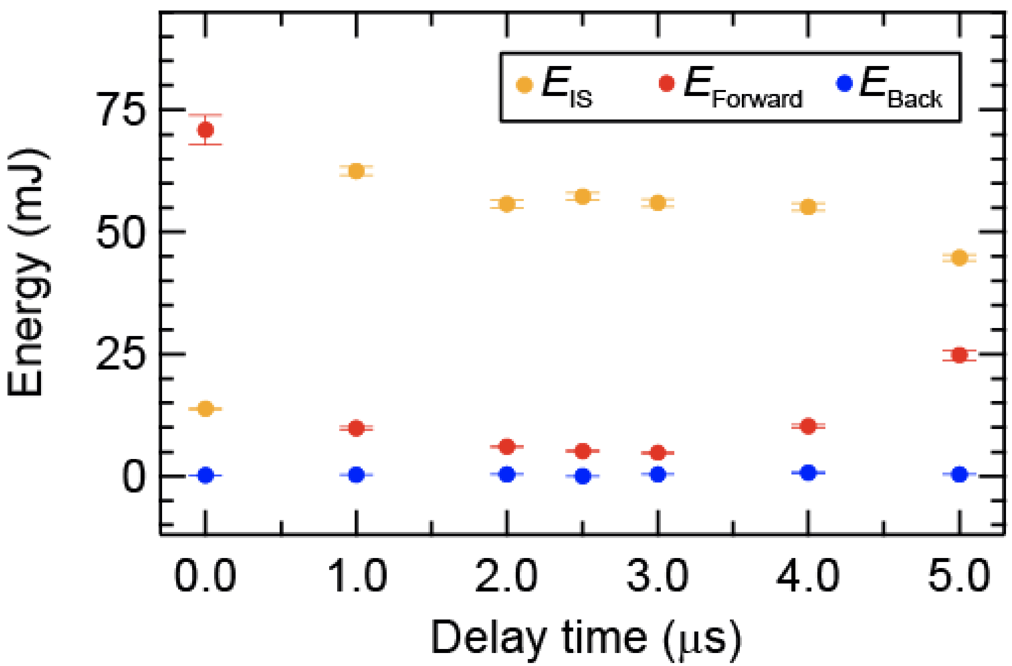
Main-pulse: λ = 10.6 μm, 14 ns, 100 mJ, ϕ 400 μm (intensity $I_{Main} = 5.7 \times 10^{9}$ W/cm^2)

Results: scattering components



Three scattering components

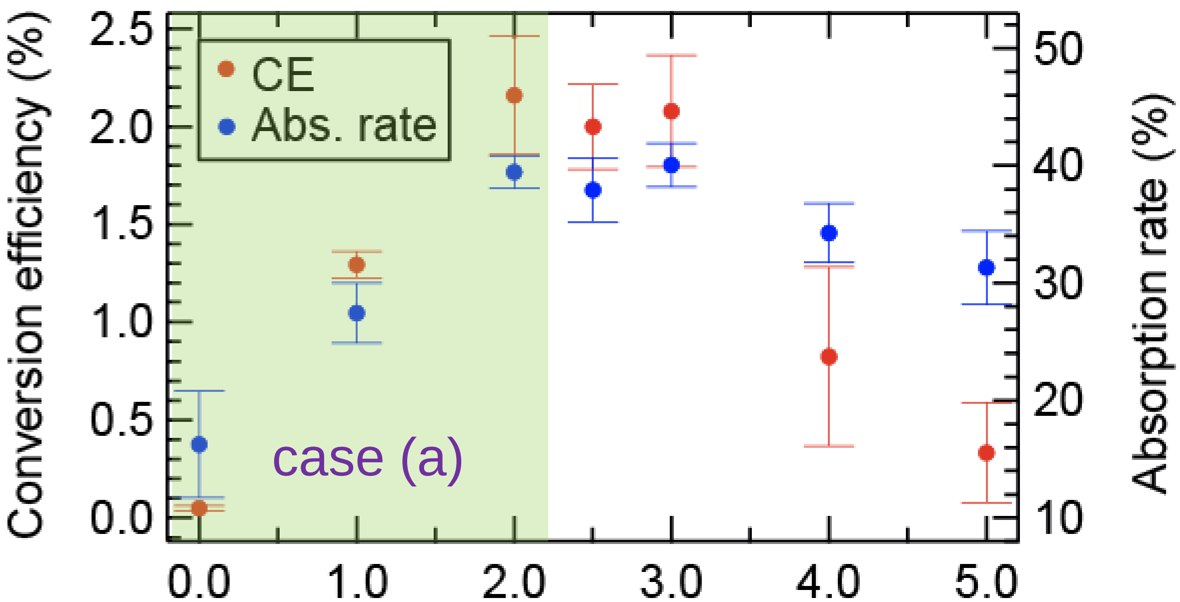
- sideward E_{IS}
- transmitted $E_{Forward}$
- backward E_{Back}

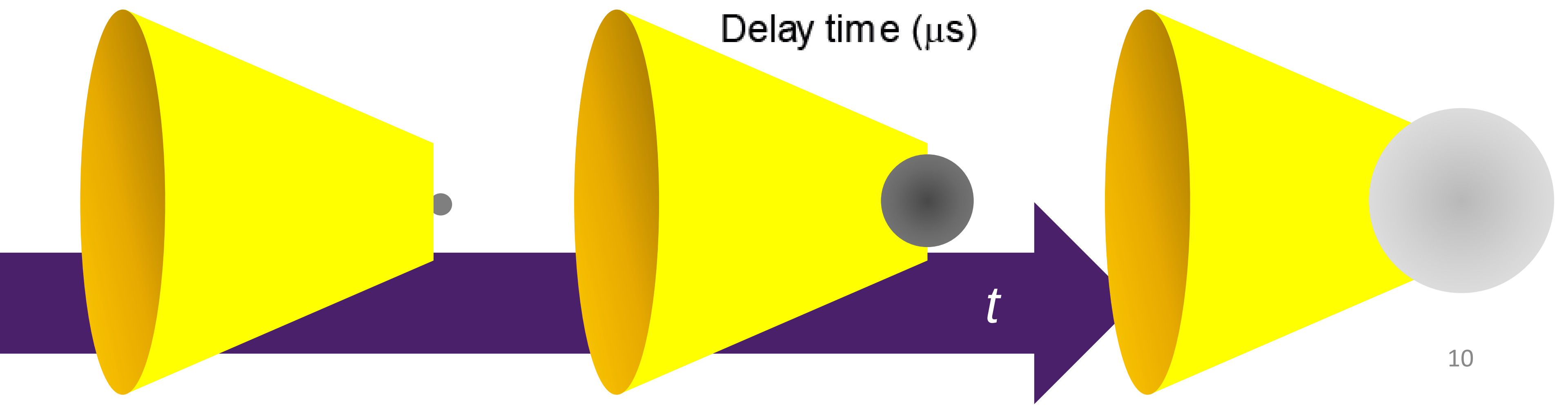


$$\text{Abs. rate} = 1 - \frac{I_{specular} + I_{scattered}}{I_{laser}}$$

$$= 1 - \frac{E_{IS} + E_{Forward} + E_{Back}}{E_{Laser}}$$

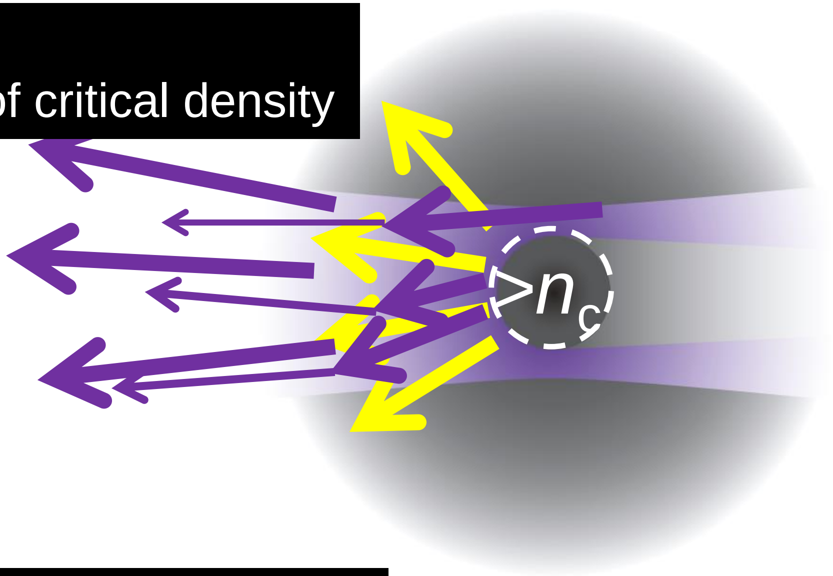
Absorption rate correlates with CE strongly ,but CE decreases rapidly for longer interval



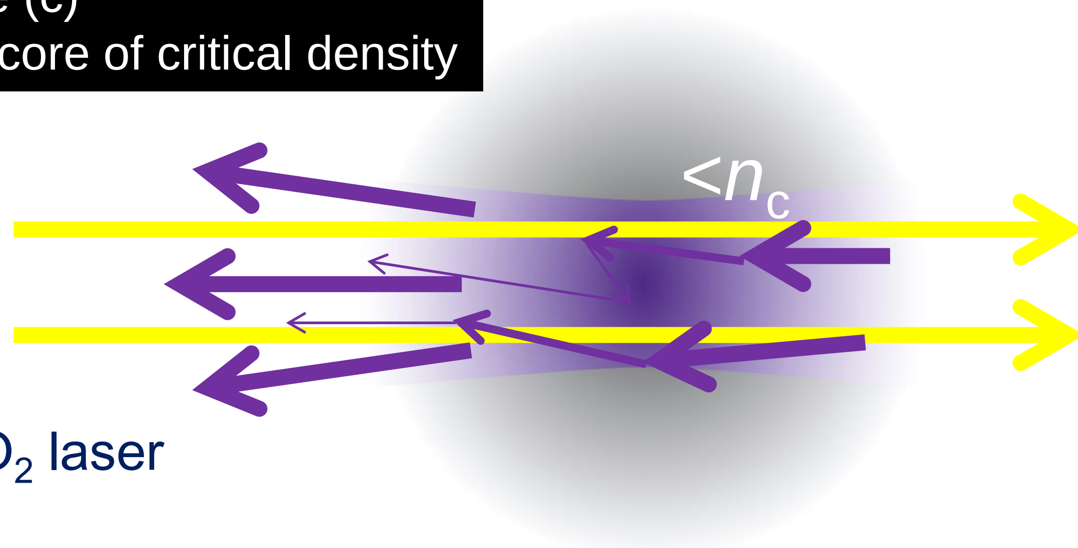


CE decreases with longer interval of double pulses

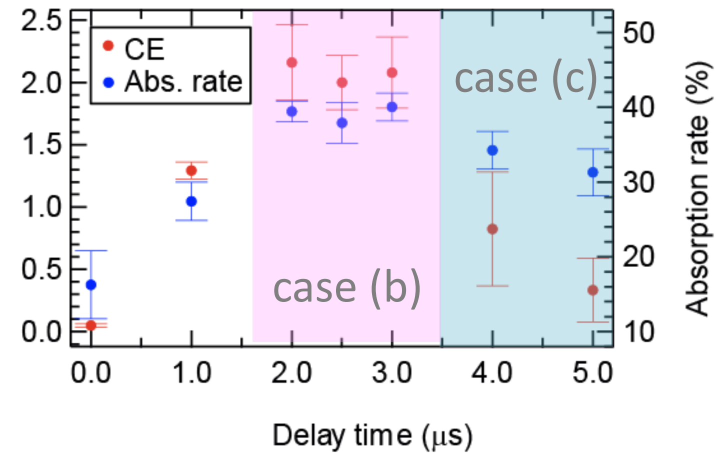
case (b)
w/ core of critical density



case (c)
w/o core of critical density



CO_2 laser



Laser penetrates deeper

Generation of optical thick plasma for EUV

EUV is converted to kinetic energy

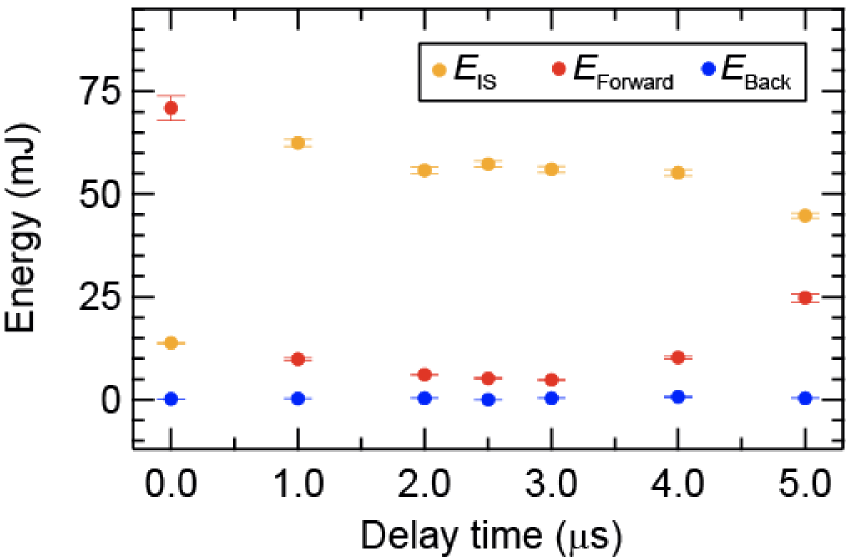
Decreasing effective EUV

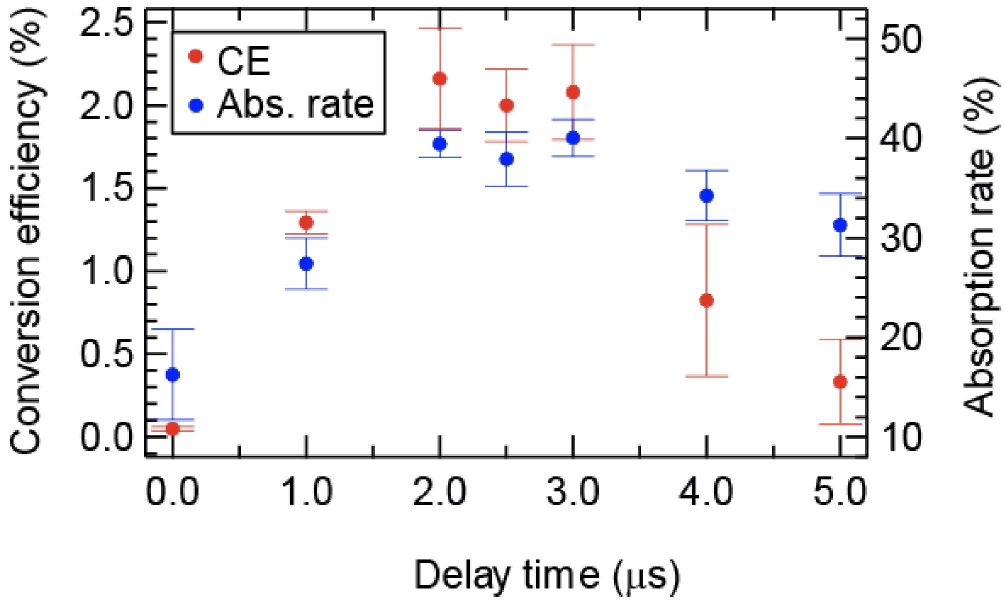
Summary

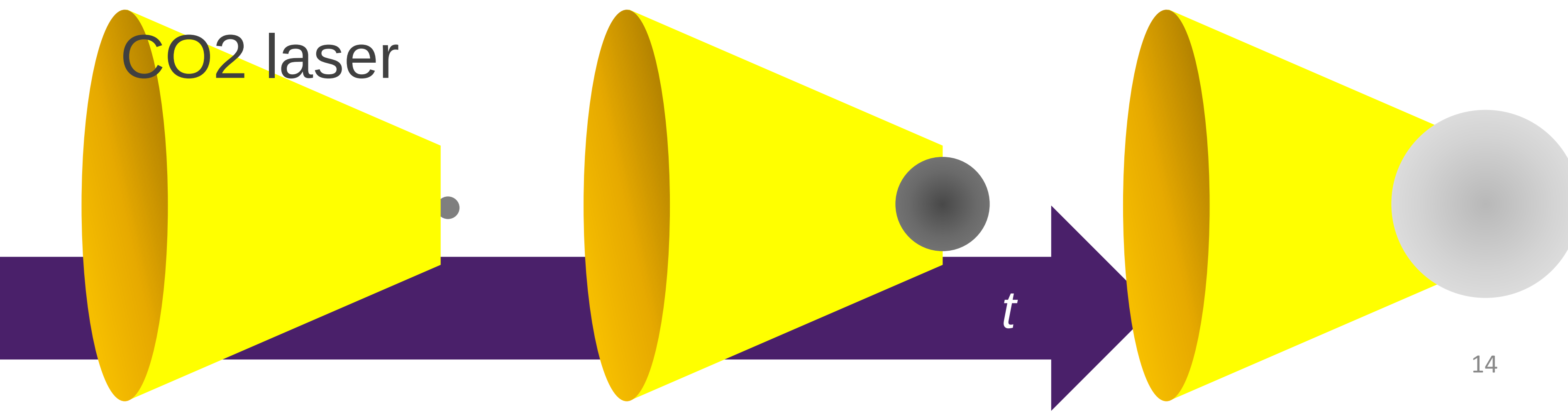
- ☑ To study correlation between laser absorption rate and CE, we developed an integrating sphere for CO_2 laser
- ☑ EUV CE at 13.5 nm and the drive laser absorption rate was measured
- ☑ It is effective for improving EUV CE to increase laser absorption rate.
- ☑ Optimization of optical depth is also necessary
- ☑ A density of plasma core should be larger than critical density of drive laser for increasing absorption rate and decreasing optical depth

Appendix

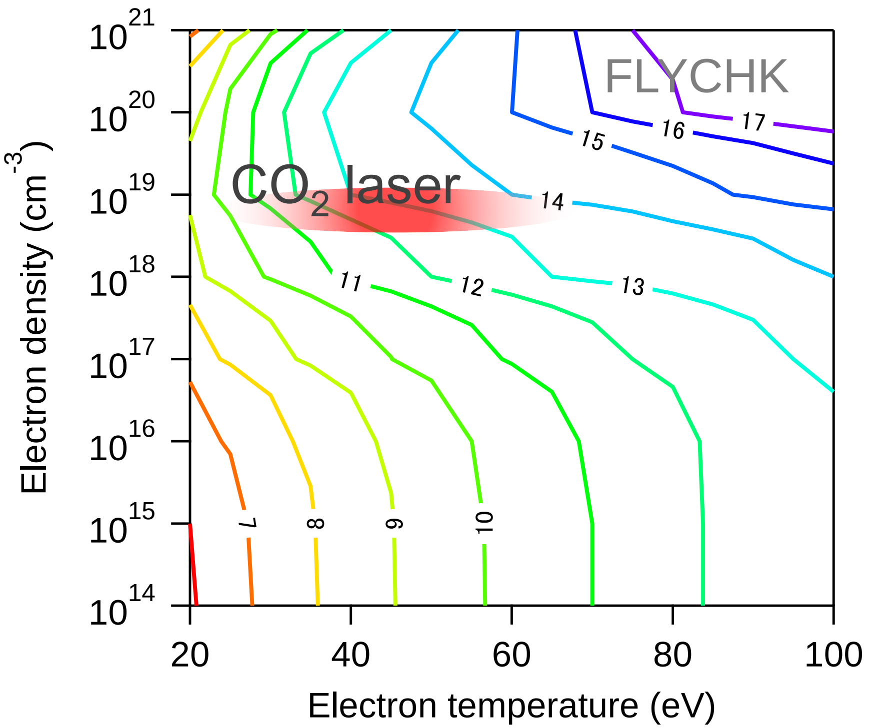
Scattering direction

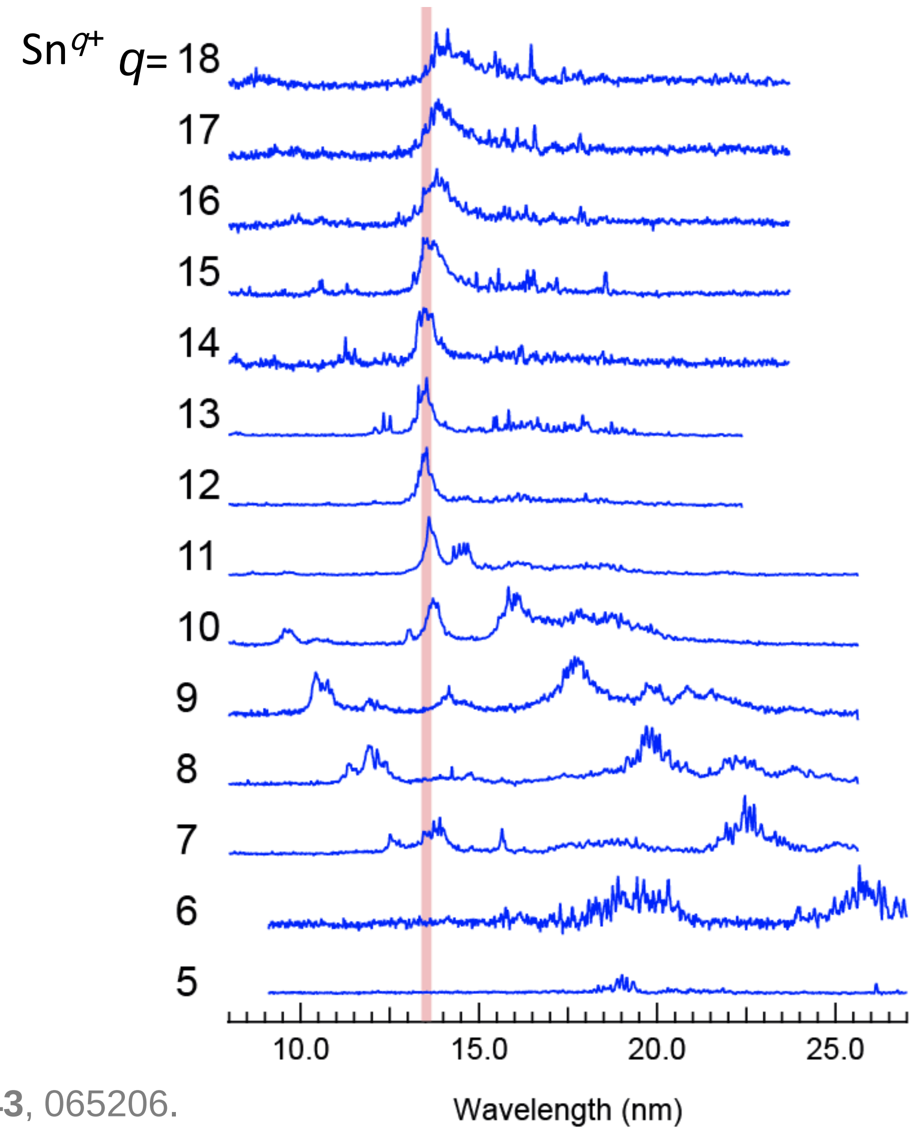






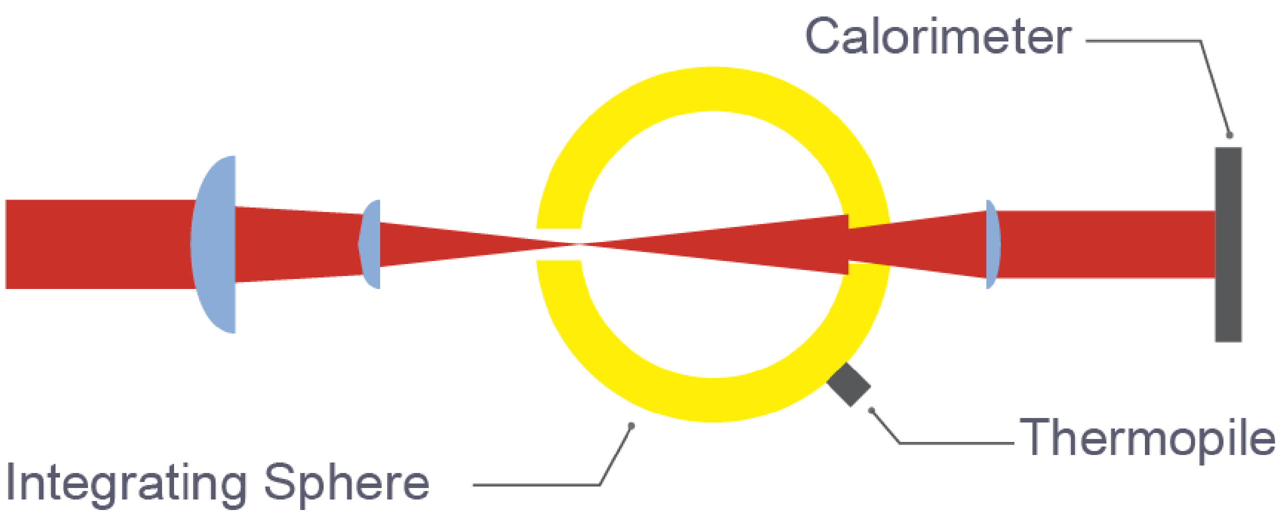
Unresolved transition array at 13.5 nm

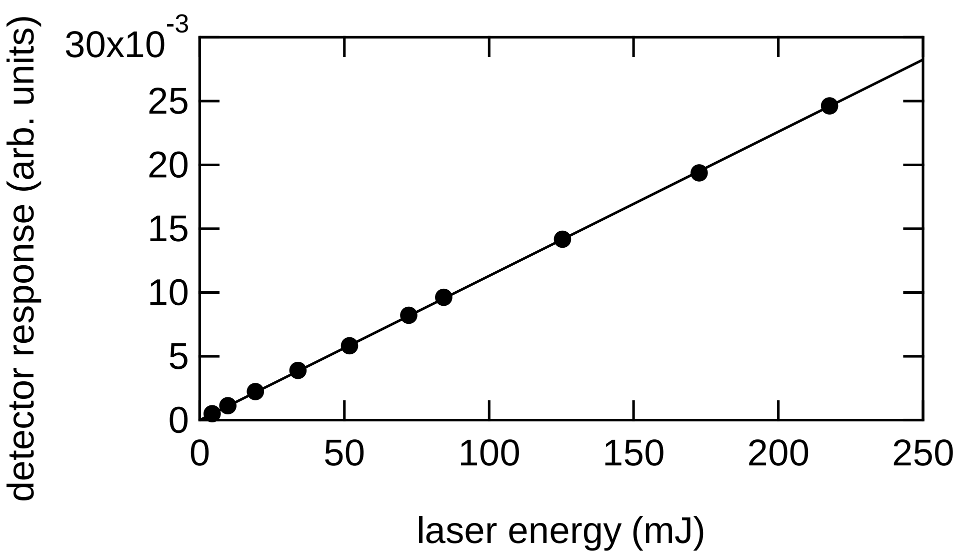




*H. Ohashi *et al.*, *J.Phys.B*, **43**, 065206.

Calibration





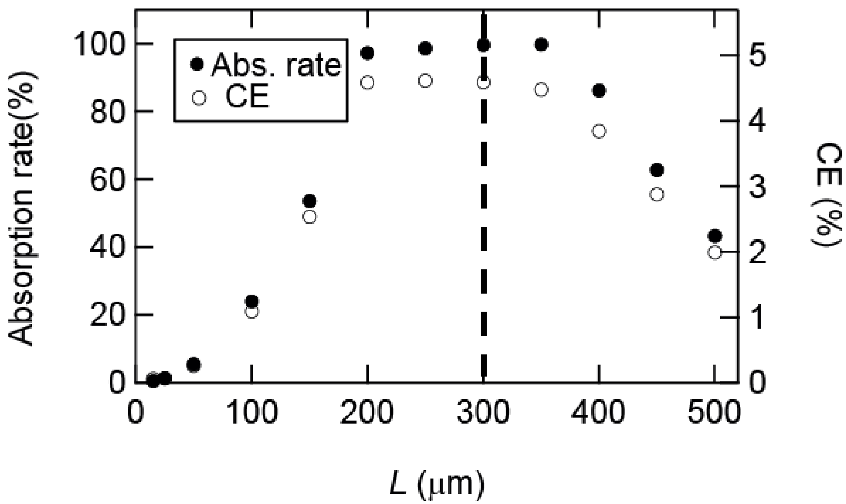
Comarison with Simulation

Assuming Gaussian profile of initial ion density

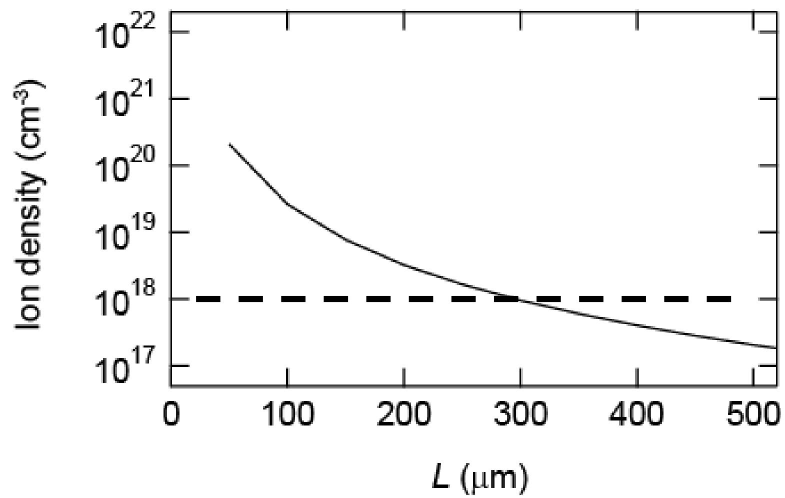
$$\rho(r) = \rho_0(L)\exp\left\{-(r/L)^2\right\}$$

$$\int_0^\infty \rho_0(L)\exp\left\{-(r/L)^2\right\}\times 4\pi r^2 \mathrm{d}r = N$$

1-D simulation results



Density of center

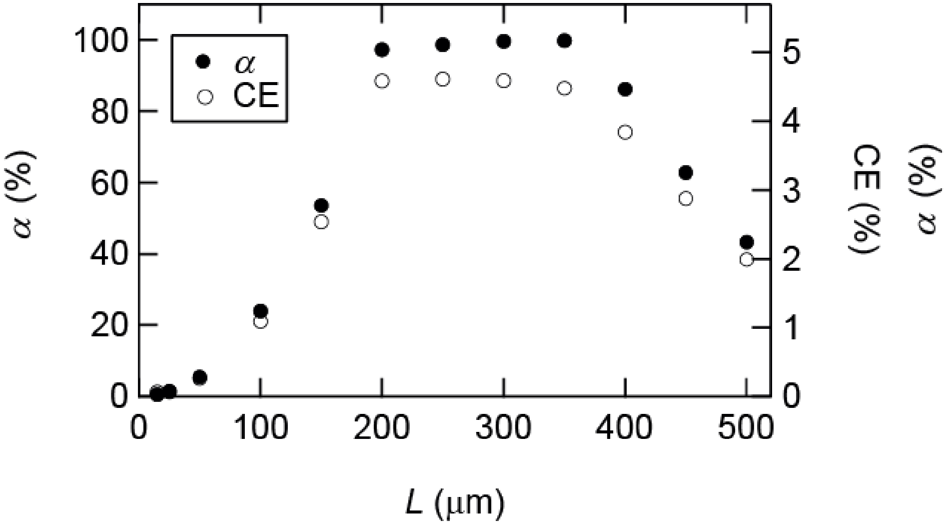


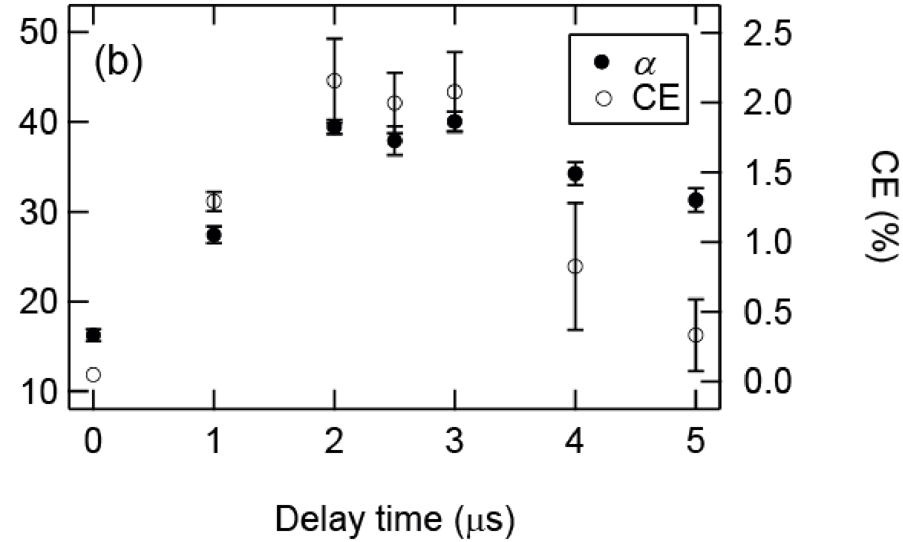
10―15 times ionized tin emits EUV

→critical density for CO_2 laser is estimated around 10^{18} cm^{-3} of ion density

→laser transmits plasma

Comparison with simulation





Twice larger than experimental results